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Application of spatially varying storage capacity model for runoff parameterization in semi-arid catchment

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Abstract: This paper introduces the method of designation of water storage capacity for each grid cell within a catchment, which considers topography, vegetation and soil synthetically. For the purpose of hydrological process simulation in semi-arid regions, a spatially varying storage capacity (VSC) model was developed based on the spatial distribution of water storage capacity and the vertical hybrid runoff mechanism. To verify the applicability of the VSC model, both the VSC model and a hybrid runoff model were used to simulate daily runoff processes in the catchment upstream of the Dianzi hydrological station from 1973 to 1979. The results showed that the annual average Nash-Sutcliffe coefficient was 0.80 for the VSC model, and only 0.67 for the hybrid runoff model. The higher annual average Nash-Sutcliffe coefficient of the VSC model means that this hydrological model can better simulate daily runoff processes in semi-arid regions. Furthermore, as a distributed hydrological model, the VSC model can be applied in regional water resource management.

Key words: VSC model; hybrid runoff model; water storage capacity; semi-arid region

1 Introduction

The study of hydrological process simulation in arid and semi-arid regions is now a hot topic in hydrological science. Zhao (1992) put forward the Shanbei model to simulate runoff processes in arid areas. Hu et al. (2004) developed a runoff-evaporation hydrological model for arid plain oases. Bao and Wang (1997) utilized a vertically mixed runoff model to simulate the Douhe Reservoir watershed, and found that it had a higher precision in semi-arid regions. Wang and Zhou (1998) improved the Xin'anjiang model by applying a mixed runoff mechanism. They used the improved model in three sub-catchments of the Yongding River Watershed and obtained good results. Jia et al. (2006) developed a distributed model of the hydrological cycle system in the Heihe River Basin and obtained good results. Liu et al. (2006) developed the TsingHua integrated hydrological modeling system for small watersheds

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(THIHMS-SW) and applied it in the Chabagou Basin. These studies were mainly concentrated in the northwest inland of China and the Yellow River Basin/Loess Plateau. There is less related research from the northeast semi-arid regions of China. In the present study, in order to simulate the hydrological process in semi-arid regions, a VSC model was developed based on the spatial distribution of water storage capacity. A full-fledged hybrid runoff model was applied in the study area for comparison with the VSC model, in order to verify the VSC model's applicability.

2 VSC model

2.1 Spatially distributed model of catchment water storage capacity

The spatially distributed model of catchment water storage capacity was developed on the basis of the Xin'anjiang model (Zhao 1992) and TOPMODEL (Beven and Kirkby 1979; Beven and Binley 1992; Beven 1997). According to the spatial pattern of vegetation rooting depth and different kinds of soil moisture parameters, the spatial distribution of catchment water storage capacity was described. The authors want to highlight two concepts: grid tension water storage capacity and grid free water storage capacity. The grid tension water storage capacity of different points in a catchment can be calculated using grid vegetation rooting depth and field moisture capacity. It is assumed that the grid free water storage capacity is a function of the grid tension water storage capacity. The root system of vegetation is a complicated system characterized by the uneven spatial distribution of rooting depth in the catchment and the constraint placed upon it by soil layers. To solve this problem, data of different kinds of vegetation rooting depth were acquired. Based on this data, the spatial distribution of vegetation rooting depth was described with the upper critical slope gradient, lower critical slope gradient and critical soil layer depth.

The critical soil layer depth is a function of the characteristic rooting depth of vegetation:

$$L_1 = \kappa Z_{rc} \quad (1)$$

where L_1 is the critical soil layer depth (mm), κ is a parameter, and Z_{rc} is the characteristic rooting depth of vegetation (mm). The vegetation rooting depth can be calculated as follows:

$$Z_r = \begin{cases} L_1 & \theta \geq \theta_1 \\ \frac{(\theta - \theta_1)}{(\theta_1 - \theta_2)} (Z_{rc} - L_1) + L_1 & \theta_2 < \theta < \theta_1 \\ Z_{rc} & \theta \leq \theta_2 \end{cases} \quad (2)$$

where Z_r is the vegetation rooting depth (mm), θ is the slope gradient ($^\circ$), θ_1 is the upper critical slope gradient ($^\circ$), and θ_2 is the lower critical slope gradient ($^\circ$).

Grid tension water storage capacity is the product of grid vegetation rooting depth and grid field moisture capacity, as shown in Eq. (3):

$$S_c = \phi Z_{rg} \quad (3)$$

where S_c is the grid tension water storage capacity (mm), ϕ is the grid field moisture capacity,

and Z_{rg} is the grid vegetation rooting depth (mm), which can be calculated with Eq. (2).

Grid free water storage capacity is affected by soil type and grid vegetation rooting depth. It is assumed that the grid free water storage capacity is a function of grid tension water storage capacity:

$$S = \beta S_c \quad (4)$$

where S is the grid free water storage capacity (mm), and β is a parameter.

2.2 Grid hybrid runoff model

Based on the spatial distribution of water storage capacity and the vertical hybrid runoff mechanism, the VSC model was developed. In the VSC model, the surface runoff is first derived from the net rainfall using the simplified Green-Ampt equation (Bao and Wang 1997); the remaining water sinks into the soil, which increases the soil water content. When the soil water content is larger than the grid tension water storage capacity, the excess water becomes runoff. When the runoff is more than the grid free water storage capacity, the excess water flows out of the land surface and becomes surface runoff, meanwhile, interflow and groundwater runoff are generated. When the runoff is lower than the grid free water storage capacity, interflow and groundwater runoff are generated. Under these conditions, the free water storage can be divided into the interflow and groundwater runoff.

When the net rainfall is more than the actual infiltration quantity, surface runoff is generated:

$$R_s = P - F_A \quad (5)$$

$$F_A = \begin{cases} F_M & P \geq F_M \\ P & P < F_M \end{cases} \quad (6)$$

$$F_M = F_C (1 + K_F \frac{S_c - S_0}{S_c}) \quad (7)$$

where R_s is the surface runoff (mm), P is the net rainfall (mm), F_A is the actual infiltration quantity (mm), F_M is the infiltration capacity (mm), F_C is the steady infiltration capacity (mm), K_F is the sensitivity coefficient of the soil moisture deficiency's influence on the infiltration capacity, and S_0 is the soil water content (mm).

When the runoff is higher than the grid free water storage capacity, the excess water flows out of the land surface and becomes surface runoff, and the grid free water storage is equal to the grid free water storage capacity:

$$\begin{cases} R_s = R - S \\ S_s = S \end{cases} \quad (8)$$

where R is the runoff (mm), and S_s is the grid free water storage (mm).

When the runoff is lower than the grid free water storage capacity, interflow and groundwater runoff are generated. The grid free water storage can be calculated with the following equation:

$$S_s = R \quad (9)$$

The interflow and groundwater runoff can be calculated as follows:

$$R_I = K_I S_s \quad (10)$$

$$R_G = K_G S_s \quad (11)$$

where R_I is the volume of interflow (mm), R_G is the volume of groundwater runoff (mm), K_I is the outflow coefficient of free water storage to interflow, and K_G is the outflow coefficient of free water storage to groundwater runoff.

The temperature-index approach (Takeuchi et al. 1999; Ao et al. 2006) was used to simulate the processes of snow accumulation and snow melt. The canopy interception module was built under the following hypothesis: rain first falls on the vegetation canopy, and when the canopy interception volume reaches its maximum capacity, the remaining rain passes through the vegetation and reaches the ground (Wigmosta et al. 1994). The two-source evapotranspiration model developed by Mo et al. (2004) was used to directly compute the actual evapotranspiration from vegetation and soil. Surface runoff flowed into the lower river reaches, the concentration of interflow and groundwater runoff was simulated with a linear reservoir (Zhao 1992), and the flow in the river channel was routed with the Muskingum method.

3. Study area and data collection

3.1 Description of study area

The Laoha River Basin is located in northeast China. The basin elevation varies between 444 m and 1 836 m. The terrain tilts from the southwest to the northeast. The basin lies in the temperate and semi-arid continental monsoon climate zone. Multi-year mean rainfall is about 450 mm. The main vegetation types are grassland and agricultural crops. Annual precipitation is mainly concentrated in the flood season (from June to September), which accounts for more than 80% of total annual precipitation. Evaporation is substantial, and the average annual land surface evaporation is about 1 600-2 500 mm. The annual average maximum and minimum temperatures are 14°C and 2°C, respectively. The maximum temperature ranges from -4°C in January to 29°C in July, and the minimum temperature ranges from -16°C in January to 18°C in July.

The studied catchment lies in the southern part of the Laoha River Basin and has an area of 1 643 km². The Dianzi hydrologic station (41°25'N, 118°50'E) is located at the outlet of the catchment. There are a total of ten precipitation stations and three evaporation stations in the catchment. The catchment has a large amount forest cover, a low temperature, and an annual average precipitation of about 520 mm.

3.2 Data collection

The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model (DEM) data from the National Geophysical Data Center (NGDC) was used to describe the topography in the catchment upstream of the Dianzi hydrological station. The DEM data had

56 rows and 81 columns with a resolution of 30 s. After the depressions in the DEM were treated, the flow direction and catchment area were calculated, and the catchment boundary was determined.

University of Maryland (UMD) one-kilometer global land cover data were used to determine local land cover conditions. There are 14 land cover types in the UMD classification system. The data's resolution is 1 km. There are nine land cover types in the catchment upstream of the Dianzi station (Fig. 1).

The United Nations Food and Agriculture Organization (FAO) soil map (FAO 1995) is the source of soil type data for this study. It has a resolution of 1 km. There are three soil types in the catchment upstream of the Dianzi station (Fig. 2). They were converted into two types through the United States Department of Agriculture (USDA) soil triangular diagram: sandy clay loam and clay loam. The field moisture capacity of sandy clay loam is $0.27 \text{ mm}^3/\text{mm}^3$, and the field moisture capacity of clay loam is $0.34 \text{ mm}^3/\text{mm}^3$.

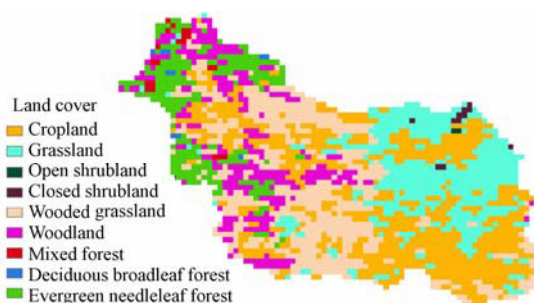


Fig. 1 Land covers in catchment upstream of Dianzi station

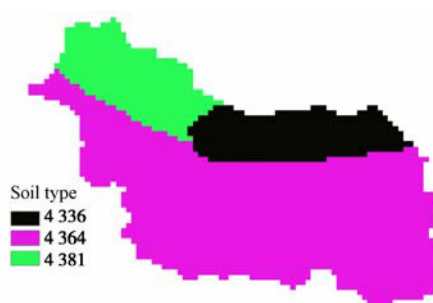


Fig. 2 Soil types in catchment upstream of Dianzi station

The China Meteorological Bureau provided related meteorological data, including mean temperature, maximum temperature, minimum temperature, annual hours of sunshine, mean wind speed, mean water vapor pressure, and mean precipitation.

4 Application

To verify the applicability of the VSC model, both the VSC model and the hybrid runoff model (Hu et al. 2005; Ren et al. 2008) were applied in the catchment upstream of the Dianzi station to simulate daily runoff processes from 1973 to 1979.

4.1 Parameter calibration

The VSC model is a conceptual distributed hydrological model. In the VSC model, some parameters with physical meanings can be acquired through remote sensing data or field observation; some parameters need to be determined through parameter calibration. The hybrid runoff model is a traditional conceptual hydrological model, and all the parameters in the model need to be determined through parameter calibration. The particle swarm optimization

algorithm (Kennedy and Eberhart 1995) was used to calibrate parameters in this study.

The error of the total runoff volume and Nash-Sutcliffe coefficient were considered the object functions of parameter calibration. The model calibration period extended from 1973 to 1977, and the model verification period extended from 1978 to 1979. Parameters of the VSC model and the hybrid runoff model are shown in Table 1 and Table 2, respectively.

Table 1 Calibrated parameters of VSC model

Parameter	β	κ	θ_1 (°)	θ_2 (°)	K_I	K_G	C_1	C_G	F_C (mm)	K_F	K_E (h)	X_E
Value	0.40	0.05	8.60	6.43	0.41	0.34	0.86	0.9992	93.38	1.73	22.50	0.46

In Table 1, C_1 and C_G are the decay constants of interflow and groundwater runoff, respectively, K_E is the storage constant, and X_E is the flow weight factor.

Table 2 Calibrated parameters of hybrid runoff model

Parameter	k_c	W_U (mm)	W_L (mm)	W_D (mm)	b	b_x	f_0 (mm)	F_C (mm)	K	K_G	i_m	x
Value	0.67	20	80	50	0.48	0.53	18	11	0.88	0.85	0.042	0.18

In Table 2, k_c is the evapotranspiration coefficient, W_U is the upper layer tension water capacity, W_L is the lower layer tension water capacity, W_D is the deep layer tension water capacity; b is the index of the tension water storage capacity curve, b_x is the parabolic index of the spatial infiltration capacity distribution curve, f_0 is the average maximum infiltration capacity of the catchment, K is the decay coefficient of the Horton infiltration equation, i_m is the impermeable area ratio, and x is the calculation coefficient for the Muskingum method.

4.2 Simulation result analysis

The contrast between discharges simulated by the hybrid runoff model and VSC model and the observed discharges are shown in Fig. 3 and Fig. 4. The simulated discharge processes of the two models are in agreement with the observed ones. The VSC model was more precise than the hybrid runoff model except in a few periods. This indicates that the VSC model is superior to the hybrid runoff model.

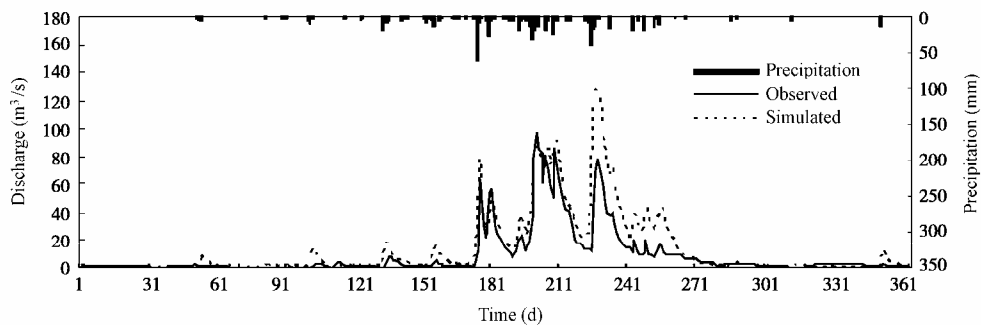


Fig. 3 Simulated discharge of hybrid runoff model vs. observed discharge in 1979

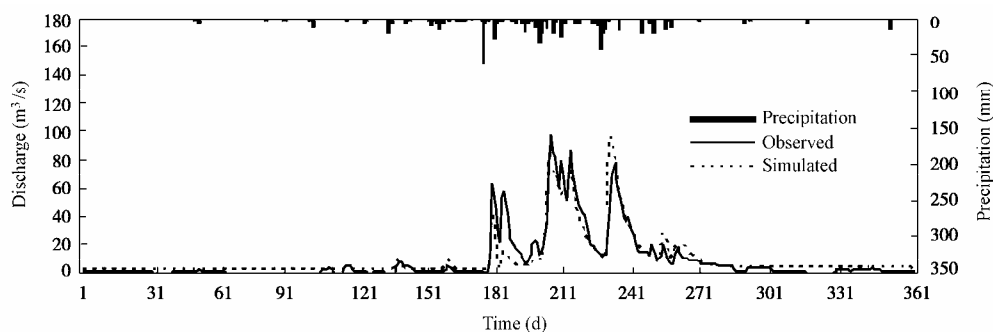


Fig. 4 Simulated discharge of VSC model vs. observed discharge in 1979

Table 3 shows Nash-Sutcliffe coefficients, absolute errors and relative errors of predicted runoff from the VSC model and hybrid runoff model. The Nash-Sutcliffe coefficient reflects the model's accuracy in representing the flood peak, and the absolute error and relative error reflect the model's accuracy in simulating the flood volume. In the daily runoff process simulation of the catchment upstream of the Dianzi station, the annual average Nash-Sutcliffe coefficient was 0.80 for the VSC model and only 0.67 for the hybrid runoff model. Generally speaking, these simulation results are acceptable for cold arid hydrological process simulation studies. In the parameter calibration period, the annual average Nash-Sutcliffe coefficient of the VSC model was higher than that of the hybrid runoff model by 11.2%; in the verification period, the annual average Nash-Sutcliffe coefficient of the VSC model was higher than that of the hybrid runoff model by 19%. These results show that both the VSC model and the hybrid runoff model can be used for simulation of the study area, and that the VSC model has better simulation results than the hybrid runoff model. The absolute errors and relative errors of runoff simulation also show that the VSC model is better than the hybrid runoff model.

Table 3 Nash-Sutcliffe coefficients, absolute errors and relative errors of predicted runoff from VSC model and hybrid runoff model

Period	Year	VSC model			Hybrid runoff model		
		Nash-Sutcliffe coefficient	Absolute error (mm)	Relative error (%)	Nash-Sutcliffe coefficient	Absolute error (mm)	Relative error (%)
Calibration period	1973	0.80	-4.69	-3.94	0.72	-29.41	-24.76
	1974	0.73	-2.24	-2.12	0.67	-6.47	-6.25
	1975	0.81	1.98	1.63	0.79	21.76	17.96
	1976	0.73	21.45	45.10	0.39	34.06	71.60
Verification period	1977	0.84	-3.87	-3.91	0.80	30.68	31.04
	1978	0.85	17.28	11.82	0.67	72.84	49.84
	1979	0.85	-2.60	-1.54	0.67	73.58	43.90

There are two reasons that the VSC model has better simulation results than the hybrid runoff model in this study area. First of all, in the VSC model, we designed a snow melt module and an evapotranspiration module, which reasonably described the snow accumulation and melt processes and the actual evapotranspiration process in cold and arid regions. The

hybrid runoff model does not have a snow melt module. Furthermore, the data source for the hybrid runoff model is observation data from an evaporation pan, so the model does not simulate the catchment evapotranspiration process precisely. Secondly, as a distributed hydrological model, the VSC model can use a variety of data sources. In the process of the VSC model construction, the impact of topography, vegetation type, soil type, soil moisture parameters and other factors of runoff was considered. As opposed to the VSC model, the hybrid runoff model is only a traditional conceptual hydrological model; it does not take into consideration the impact of characteristics of the underlying surface on runoff.

The VSC model built a direct relationship between rainfall, runoff, and the grid geomorphic unit, and more easily produced the catchment response distribution than the distributed probabilistic humidity model. The spatial distribution of the tension water storage capacity within the catchment upstream of the Dianzi station is shown in Fig. 5. In the VSC model, the influences of catchment topography, vegetation type, soil type and soil moisture parameters on the catchment tension water storage capacity were taken into account. Therefore, Fig. 5 is a reasonable depiction of the spatial distribution of tension water storage capacity in the catchment upstream of the Dianzi station.

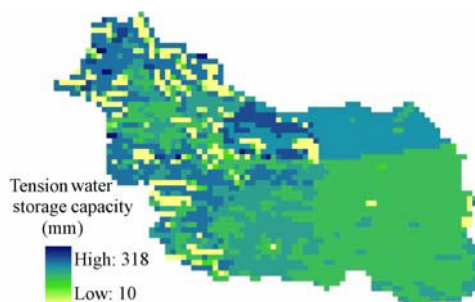


Fig. 5 Spatial distribution of tension water storage capacity in catchment upstream of Dianzi station

5 Conclusions

The VSC model was developed based on the spatial distribution of water storage capacity and the vertical hybrid runoff mechanism. It was used to simulate daily hydrological process in the catchment upstream of the Dianzi hydrological station in the Laoha River Basin. The simulation results were compared with those of the hybrid runoff model. The main conclusions are as follows:

(1) Both the VSC model and the hybrid runoff model can be used for hydrological simulation in the catchment upstream of the Dianzi station. The annual average Nash-Sutcliffe coefficient of daily runoff simulation of the VSC model was higher than that of the hybrid runoff model. The runoff amount error of the VSC model was smaller than that of the hybrid runoff model.

(2) Based on the vertical hybrid runoff mechanism, the VSC model provides a reasonable

description of runoff processes in the study area. Because it takes into consideration the hydrological characteristics of cold and arid regions, the VSC model is better than the hybrid runoff model in simulating daily runoff processes.

(3) A spatially distributed model of water storage capacity takes into account the impact of catchment topography, vegetation type, soil type, and soil moisture parameters on the catchment water storage capacity, and can reasonably describe the spatial distribution of water storage capacity.

(4) The VSC model has a simple structure, uses data from multiple sources, describes the soil water change of the grid vegetation root layer through a grid hybrid runoff mechanism, and avoids direct description of complicated soil water flow processes. The VSC model can be used for hydrological process simulation, water resources assessment, agricultural production planning, and drought forecasting in semi-arid regions.

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